SYSTEM FOR IMAGING A CROSS-SECTION OF A SUBSTRATE

This invention relates to particle beams, and in particular, to systems and methods for imaging a cross-section of a semiconductor substrate using a particle beam.

BACKGROUND

Integrated circuits frequently incorporate devices that extend deeply into a semiconductor substrate or wafer. In the manufacture of such integrated circuits, it is desirable to periodically inspect the structure of these devices. In most cases, this is achieved by inspecting a cross-section of the wafer on which the integrated circuits are formed.

The conventional method for inspecting a cross-section of a semiconductor substrate generally includes the removal of material from the substrate in order to expose a cross-sectional surface. This is followed by the illumination of that surface by an imaging beam. The step of exposing a cross-sectional surface is typically accomplished by scanning the front surface of the semiconductor substrate with a focused ion-beam to excavate a trench. The vertical wall of this trench forms the cross-sectional surface to be imaged by the imaging beam.

The imaging beam is typically a particle beam that scans the cross-sectional surface exposed by the scanning focused ion-beam. The interaction of this particle beam with the cross-sectional surface results in the emission of charged particles. These charged particles are detected by a detector that provides data to a processor for transformation of the data into a cross-sectional image of the semiconductor substrate.

A disadvantage of the foregoing method of obtaining a cross-sectional image is that the cross-sectional surface is exposed point by point using a focused ion-beam. Because the ion-beam is focused to a small point, the source of ions must be one that is capable of providing a large ion current in a small area. Such sources, which are referred to as "bright" sources, typically use, as a source of ions, a metal that is liquid at or slightly above room temperature. For brevity, we refer to such metals as "liquid metals." Of these liquid metals, the one generally considered most practical, because of its high boiling point, is gallium.

Unfortunately, it is extremely undesirable to introduce stray metal ions, such as gallium, into the semiconductor fabrication process. The presence of even small amounts of metal ion left on a semiconductor substrate following exposure to a focused ion beam can, through diffusion, contaminate other circuits formed on that substrate. As a result,

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following inspection of the cross-section of a wafer, the entire wafer is routinely discarded.

It is therefore desirable in the art to provide a method and system for imaging a cross-section of a substrate but without the deposition of stray metal ions on the substrate.

SUMMARY

A system according to the invention excavates a trench on the substrate by projecting an image of an aperture onto the substrate instead of by scanning a focused ion beam across the substrate. This relieves the constraint that the ion source be a bright source and opens the door to the use of an ion source other than a liquid metal source.

More particularly, in a system embodying the invention, the cross-sectional surface to be imaged is exposed by projecting an ion beam image of an aperture onto the front surface of a workpiece. This workpiece is typically a semiconductor substrate, or wafer. Because the ion beam source is not focused directly on the front surface of the workpiece, the constraints on the brightness of the ion source are considerably relaxed. In particular, in a system incorporating the principles of the invention, one can generate an ion beam with an ion source other than a liquid metal source. Because of the reduced risk of contamination by stray metal ions, the system of the invention is thus particularly suited for cross-sectional imaging of semiconductor wafers.

A system according to the invention includes a shaped-beam ion- projection column extending along a first axis. The ion-projection column illuminates the workpiece with an image of an aperture and thereby excavates a section of the workpiece having the size and shape of the aperture as projected by the ion-projection column, including any magnification factor. A vertical wall of the excavated section of the workpiece forms a cross-sectional surface that is then illuminated by a focused particle-beam generated by a focused-particle-beam column. The focused-particle beam column is oriented along a second axis that intersects the first axis at a predetermined angle. This predetermined angle can be either fixed or adjustable by a system operator.

The focused-particle-beam column can be either a scanning electron-microscope, in which case the focused particle-beam is a beam of electrons, or a scanning focused ion beam column, in which case the focused particle-beam is an ion beam.

The ion source in the shaped-beam ion-projection column can be a relatively low brightness source. Such low brightness sources are typically characterized by a brightness of less than 100,000 amps per square centimeter per steradian. These low brightness sources can be plasma sources, or surface plasma sources. However, the ion source can also be a liquid metal source such as a gallium source.

The shaped-beam ion-projection column can include a mask having an aperture in the shape of the region to be excavated. The mask is typically disposed between the ion source and the wafer surface. While the aperture can be any shape, it is preferable that the aperture have at least one straight edge for forming an easily imaged cross-sectional surface.

In practice, the edges of the aperture cannot be made perfectly smooth. In order to reduce the effect of imperfections in the edge of the aperture, the apparatus of the invention further includes an optional dithering system. Such a dithering system includes deflector plates disposed between the mask and the surface of the wafer. A time-varying voltage on these deflector plates causes a time-varying electric field through which the ions forming the image of the aperture pass on their way to the wafer surface. The periodic translation of the ion beam in response to the time varying electric field through which it passes results in a periodic variation in the location of the projected image on the front surface of the workpiece. This periodic variation in the location of the projected image averages out effects of imperfections on the edge of the aperture.

In another embodiment, a workpiece support holds a workpiece at a selectable angle relative to an ion beam generated by an ion-beam column. In this embodiment, the system switches between a cutting mode and an imaging mode. In the cutting mode, the workpiece support holds the workpiece such that its front surface is normal to the ion beam. The ion-beam column then focuses an image of an aperture on the front surface to excavate a section of the workpiece having the projected size and shape of the aperture. A vertical wall of the excavated section of the workpiece forms a cross-sectional surface. In the imaging mode, the workpiece support holds the workpiece at an angle relative to the ion- beam. In this mode, the ion-beam column scans a focused ion-beam along the cross-sectional surface and thereby forms an image of that surface.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other objects, features and advantages of the invention will be apparent from the following description and the accompanying drawings, in which

FIG. 1 is a schematic illustration of a first embodiment of a cross-sectional imaging system incorporating the invention;

FIG. 2 shows the ion beam column of FIG. 1 projecting an image of an aperture onto a workpiece;

FIG. 3 shows an aperture on the workpiece as projected by the ion beam column shown in FIG. 2;

FIG. 4 is a flow chart illustrating steps followed by the system of FIG. 1 in imaging a cross-section of the workpiece shown in FIG. 3;

FIG. 5 shows a second embodiment of a cross-sectional imaging system operating in a cutting mode in which the workpiece surface is normal to an ion beam;

FIG. 6 shows the system of FIG. 5 operated in an imaging mode in which the workpiece surface is tilted relative to the ion beam; and

FIG. 7 is a flow chart illustrating steps followed by the system of FIGS. 5 and 6 in imaging a cross-section of a workpiece.

DETAILED DESCRIPTION

A particle-beam system **10** for obtaining an image of a cross-section of a workpiece **11**, as shown in FIG. 1, includes a shaped-beam ion-projection column **12** configured to project an image of an aperture onto the front surface **14** of the workpiece **11**. Preferably, the projection column **12** is oriented along a first axis **18** normal to the front surface **14** of the workpiece **11** such that the ion beam is at normal incidence to that front surface **14**.

The system **10** further includes a focused-particle-beam imaging column **20** oriented along a second axis **22** that is canted relative to the first axis **18** so that it intersects the first axis **18** at a selected angle. The selected angle is other than ninety degrees and is preferably selected to be between thirty and sixty degrees. However, the invention includes the use of other non-right angles.

The workpiece **11** is mounted on a table **24** that is capable of translation in response to instructions provided by a processor **28**. The processor **28**, which also provides instructions to the projection column **12** and to the imaging column **20**, is under the control of an operator who communicates with the processor **28** by means of a user-interface **30**. The user-interface **30** is a keyboard and/or a touch-responsive display screen.

The projection column **12**, shown in more detail in FIG. 2, includes an ion source **32** that emits an ion beam colinear with the first axis **18** and in the direction of the workpiece **11**. On its way to the workpiece **11**, the ion beam passes through an aperture **34** in a mask **36**. The shape of this aperture **34** defines the shape of that region of the workpiece **11** that is to be excavated by the ion beam. The ion beam than passes through a lens system **38** that focuses an image of the aperture onto the front surface **14** workpiece **11**. In a preferred embodiment, the number and arrangement of the lenses in the lens system **38** is chosen to control the illumination and magnification of this aperture image.

The acuity of the walls of the excavated section of the workpiece **11** depends on the extent of the image blur caused by the lens system **38**. If the lens system **38** places the aperture image at optimal focus, the edge of the excavated section will be sharply defined. Otherwise, the edge will be blurred by an amount approximated by the product of the angular size of the source, as projected into the workpiece, and the extent to which the workpiece is displaced from the plane of optimal focus. The maximum allowable displacement is commonly referred to as the system's depth-of-focus.

The shape of the aperture **34** formed in the mask **36** can be rectangular, triangular, circular, or any other aperture configuration. However, it is preferable that the aperture **34** include at least one straight edge so that the resulting excavated region of the workpiece **11** has a suitably long vertical wall forming the cross-sectional surface to be imaged by the imaging column **20**.

Although the ion source **32** can be a liquid metal source, the brightness of such a source is no longer needed in order to excavate a region of the workpiece **11**. Assuming a constant ion current, the ratio of (*i*) the brightness required of a focused ion beam system to (*ii*) the brightness required of a projection beam system depends on the ratio of the area illuminated by the focused ion beam to the area of the projected aperture in the projection beam system. For a typical focused ion beam illuminating a circle with a one-hundred nanometer diameter and a typical projected aperture having linear dimensions of ten microns, the brightness requirement of the ion source is reduced by a factor of ten thousand.

Because the ion source in a projection system need not have such high brightness, a broader selection of ion sources is available for a system incorporating a projection column. In one preferred embodiment, the ion source **32** is one that does not emit trace metal ions. Such preferred sources include plasma sources, field emission gas ion sources, or surface plasma sources. Low brightness sources are typically characterized by a brightness of less than 1000 amps per square centimeter per steradian.

The selection of ion sources for the projection column **12** is constrained by the requirement that the emittance of the ion source **32** be sufficiently high to provide an ion flux suitable for excavating a region of the substrate. Emittance is the product of the ion beam's projected area and its beam convergence angle in an optical plane. The emittance required of an ion source in a projection system is typically many orders of magnitude higher than the emittance required of a probe system. An extended discussion of the concepts of emittance and brightness is found in *Principles of Electron Optics* by P. Hawkes and E. Kasper, which is hereby incorporated by reference.

In practice, the requirement of high emittance is met by providing an extended source of ions rather than a point source. Examples of extended sources suitable for practice of the invention are given in *Development of Ion Sources for Ion Projection Lithography*, Y. Lee at al., Journal of Vacuum Science and Technology, B 14(6), 3947 (1996).

Because of imperfections in the formation of an aperture **34**, the edges of the aperture **34** are not perfectly smooth. In order to mitigate the effect of any roughness in the edges of the aperture **34**, the projection column **12** optionally includes a dithering system **40** to correct for the effect of roughness on the edges of the aperture **34**.

The illustrated dithering system includes deflecting plates **42a,b** disposed between the lens system **38** and the workpiece **11**. These deflecting plates **42a,b** are connected to a signal source **44** that provides a time-varying electric field between the deflecting plates. Because the ions are charged particles, the time-varying electric field results in time-varying motion of a projected image **45** on the workpiece **11**, as shown in FIG. 3. By suitably selecting the amplitude and frequency of the signal generated by the signal source **44**, one can smooth out, or average out, the effects of imperfections in the edge of the aperture **34**, thereby simulating an aperture having perfectly smooth edges.

Preferably, the signal applied to the deflecting plates **42a,b** has an amplitude selected such that the amplitude of the dithering motion is greater than the roughness of the aperture edges. The signal frequency is selected so that the resulting excavation on the workpiece surface has substantially vertical walls. The preferred waveform generated by the signal generator **44** is a triangular wave having an amplitude and frequency consistent with the foregoing requirements.

FIG. 4 summarizes the method **46** of imaging a cross-sectional surface of a workpiece in accordance with the invention. The method includes the step of projecting an image of the aperture onto the workpiece (step **48**). This results in excavation of a region on the workpiece surface. The excavated region has a vertical wall that forms the cross-sectional surface that is later imaged by the imaging column. Optionally, a dithering subsystem smoothes the effect of any rough edges of the aperture by dithering the position of the projected aperture on the workpiece (step **50**).

After a suitable period of exposure, the ion beam is turned off (step **52**). The exposure period depends on the characteristics of the ion source, the properties of the substrate, and the desired depth of the excavated region. Suitable exposure periods are determined either by calculation, using known methods, or empirically.

The cross-sectional surface exposed by the projection column is then scanned by the focused particle-beam provided by the imaging column (step **54**). Although the focused particle-beam can be an ion-beam, the resolution of an ion-beam is significantly lower than that of an electron beam. Since the imaging column is not used for excavation of the workpiece, there is no advantage to the use of an ion beam. Hence, in the preferred embodiment, the focused particle beam for imaging the workpiece is an electron beam provided by a scanning electron microscope.

In a second embodiment of the invention, shown in FIG. 5, an ion beam column is switchable between a projection mode, for excavating the workpiece surface , and an imaging mode, for imaging the cross-section of the workpiece. In the projection mode, the ion beam column **62** projects an image of an aperture onto a workpiece **64**, thereby excavating a portion of its front surface and exposing a cross-sectional surface for imaging. The details associated with the excavation of the workpiece surface are identical to those already described in the connection with the projection column **12** of the first embodiment **10**, and need not be repeated here.

In the second embodiment **60**, a workpiece **64** is mounted on a tilting table **66** A processor **70** in communication with both the table **66** and the ion beam column **62** controls those elements in response to instructions provided by an operator by means of a user-interface **72** coupled to the processor **70**.

In operation, the ion beam column **62** is operated first in a projection mode, shown in FIG 5, in which the tilting table **66** holds the workpiece **64** such that the surface of the workpiece is normal to a column axis **74** of the ion beam column **62**. During this projection mode, the ion beam column **62** projects an image of an aperture on the workpiece **64** in a manner identical to that described above in connection with the ion beam column **12** shown in FIGS. 1 and 2. This results in the exposure of a cross-sectional surface of the workpiece.

Following the formation of a cross-sectional surface, the ion beam column **62** is operated in an imaging mode, as shown in FIG. 6. During imaging mode, the tilting table **66** holds the surface of the workpiece **64** at an angle relative to the column axis **74** of the ion beam column **62**. This tilt exposes the cross-sectional surface to a focused ion beam generated by the ion beam column **62**. Thus, in this second embodiment, the ion beam column **62** switches between projecting an image of an aperture on the workpiece **64,** and scanning a focused ion beam on the workpiece. The former mode of operation is well suited for excavating a region of the workpiece but cannot readily be used to form an image. The latter mode of operation is well suited for imaging but somewhat inefficient for excavation.

FIG. 7 summarizes the steps in a method **76** for imaging a cross-sectional surface of the workpiece using the system shown in FIGS. 5 and 6. The workpiece is first oriented so that its front surface is normal to the ion beam (step **78**). An image of the aperture is then projected onto the workpiece (step **80**). This results in excavation of a region on the workpiece surface. The excavated region has a vertical wall which forms the cross-sectional surface that is later imaged by the imaging column. To the extent that the edges of the aperture are not perfectly smooth, a dithering subsystem dithers the position of the projected aperture on the workpiece (step **82**), thereby averaging out the affect of any irregularities in the edges of the aperture.

After a suitable exposure period, the ion beam is turned off (step **84**). The exposure period depends on the characteristics of the ion source, the properties of the substrate, and the desired depth of the excavated region. Suitable exposure periods are determined either by calculation, using known methods, or empirically.

Once the cross-sectional surface has been exposed by the projection column, the workpiece is re-oriented so that its front surface intersects the ion beam at an angle (step **86**). The ion beam is now focused onto the cross-sectional surface and scanned along that surface to form the desired cross-sectional image (step **88**).

It will thus be seen that the invention efficiently attains the objects set forth above. Since certain changes may be made in the above constructions without departing from the scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all generic and specific features of the invention described herein, and all statements of the scope of the invention which as a matter of language might be said to fall there between. Having described the invention, what is claimed as new and secured by Letters Patent is: